

Effect of the Machining Processes on Low Cycle Fatigue Behavior of a Powder Metallurgy Disk Superalloy.

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A study has been performed to investigate the effect of various machining processes on fatigue life of configured low cycle fatigue specimens machined out of a NASA developed LSHR P/M nickel based disk alloy. Two types of configured specimen geometries were employed in the study. To evaluate a broach machining processes a double notch geometry was used with both notches machined using broach tooling. EDM machined notched specimens of the same configuration were tested for comparison purposes. Honing finishing process was evaluated by using a center hole specimen geometry. Comparison testing was again done using EDM machined specimens of the same geometry. The effect of these machining processes on the resulting surface roughness, residual stress distribution and microstructural damage were characterized and used in attempt to explain the low cycle fatigue results.



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TMS 2010 Annual Conference

Seattle, WA

February 17, 2010

Motivation:

- Machining induced material surface damage is a cause of a large fraction of turbine component failures and a cause of numerous aircraft accidents. High strength P/M turbine components are highly stressed and are susceptible to machining damage which can cause low cycle fatigue failures.

Approach:

- Team with an engine company to study the effect of production tooling on surface integrity and its effect on low cycle fatigue.
- Extensive characterization and quantification of the effect of machining conditions on surface/near surface material response. QUANTIFY DAMAGE.
- Measure surface roughness for each specimen tested.
- Measure induced residual stresses for each machining condition.
- Measure % cold work for each machining condition.
- Perform a detailed quantitative fractographic evaluation of each LCF failure.
- Configured LCF specimen machined using production tooling.
- Select one relevant test condition for LCF testing.
- Perform **Multiple** repeats of LCF tests for each machining condition.
- Use statistical modeling to determine and model the key machining and material variables which control low cycle fatigue response.



Configured Broached LCF Specimen Extraction and Testing



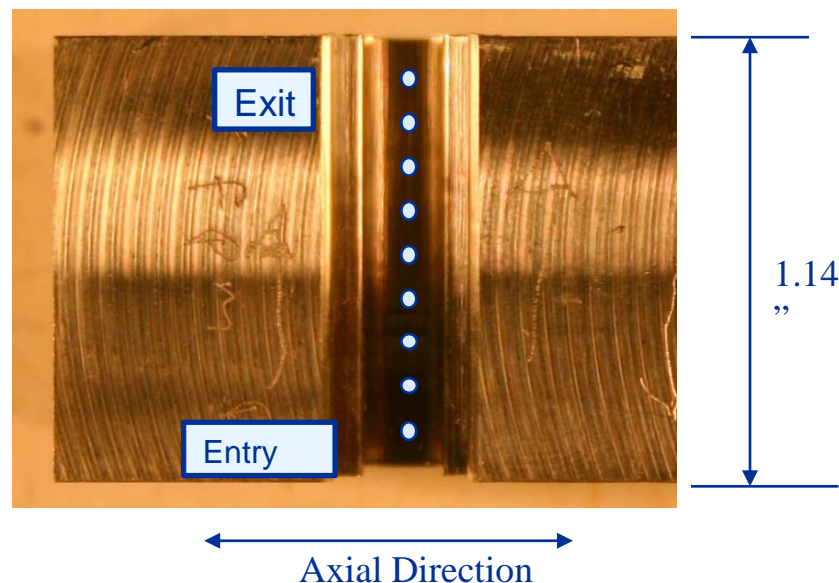
- Material: NASA's LSHR P/M alloy
- Fine Grain, Subsolvus Heat Treatment
- Test Temperature: 1200°F
- Max Stress: 140 ksi; R=0.05
- Frequency: 0.333 Hz for 24 hrs; 5 Hz
- 4 to 8 repeats per condition; additional tests in progress.

- **Broaching performed at Honeywell using production tooling.**
- Broach blank representative of full thickness disk rim.
- LCF specimens extracted by wire EDM and ground to final dimensions.
- Each specimen represents different location along broach length.

Broaching variables evaluated:

- 1) Tool Wear:** a) Sharp (newly re-sharpened) b) Dull (pre-designated number of broaching operations reached)
- 2) Broaching Speed:** a) Slow; b) Medium c) Fast (Variation in speed >> actual practice)

Characterization of Residual Stresses and Cold Work

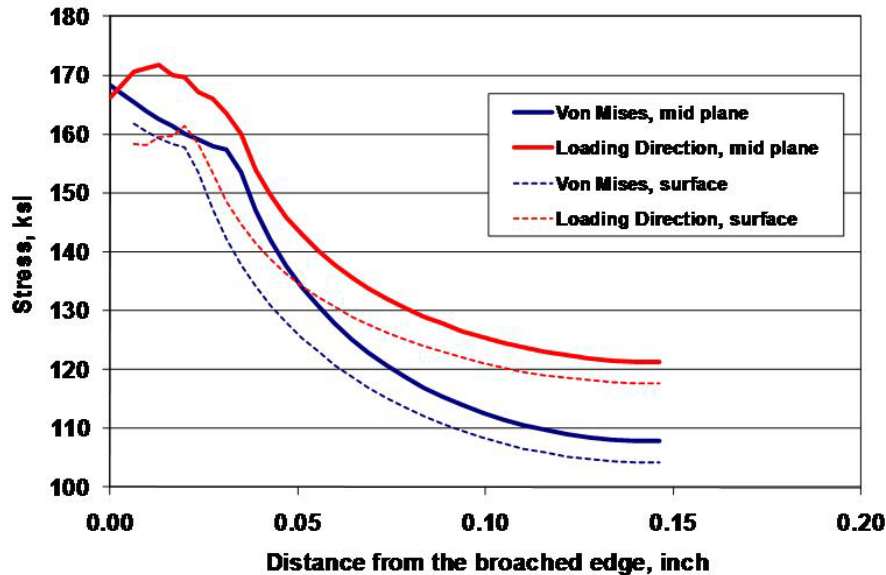


- Residual stresses and cold work were measured for each of six broaching conditions as a function of distance from the tool entry at three parallel locations (30 measurements per blank).
- Based on surface measurements, two locations with the highest and lowest residual stresses were selected for depth profile measurements.
- Residual stress measured in the axial direction.

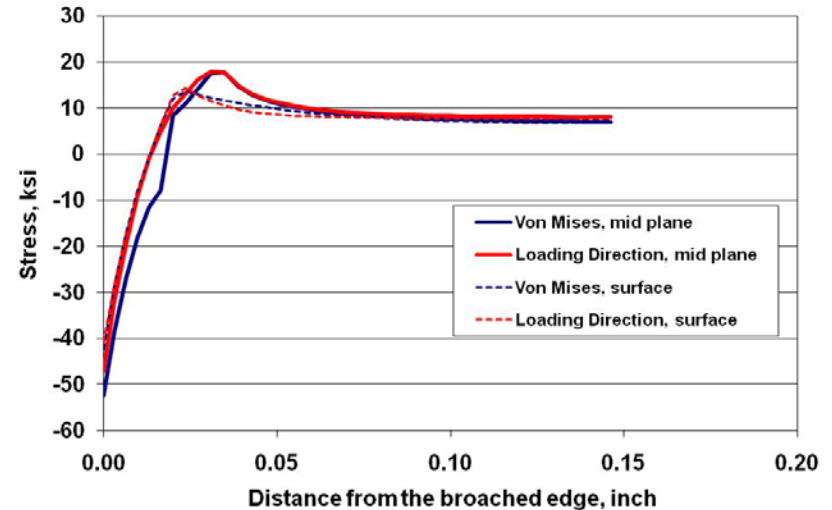
Finite Element Analysis of the Broached LCF Specimen



Broached Specimen
140 ksi Net Stress, T8 data, at 1200 F

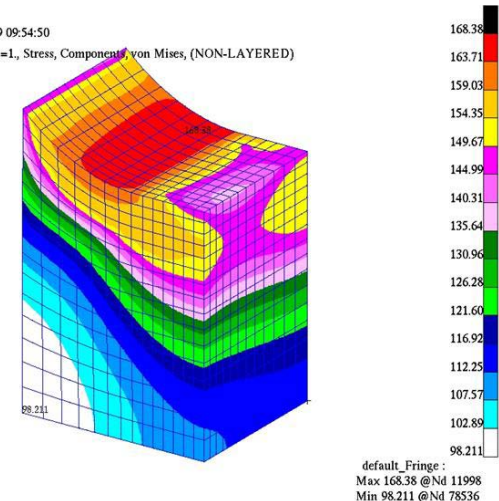


Broached Specimen
7 ksi Net Stress unloading, T8 data, at 1200 F

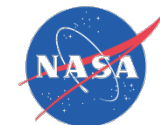


- 3D FEM elasto-plastic analysis performed of the contoured LCF specimen.
- Max loading direction stresses are below the surface.
- Due to notch plasticity substantial compressive stresses form on unloading.

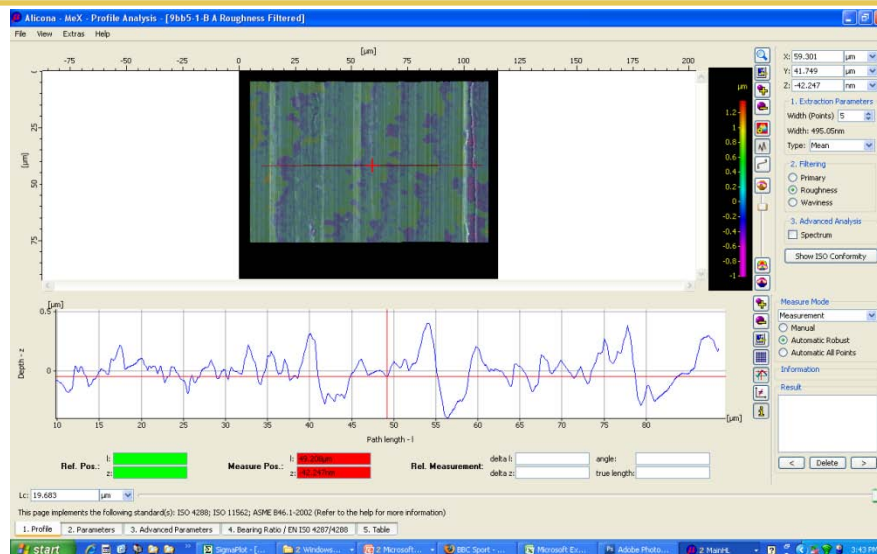
MSC.Patran 2005 r2 13-Mar-09 09:54:50
Fringe: Static, Step1, TotalTime=1, Stress, Component, von Mises, (NON-LAYERED)



$K_t = 1.6$ (elastic)



Roughness Analysis of Broached Surface Finish

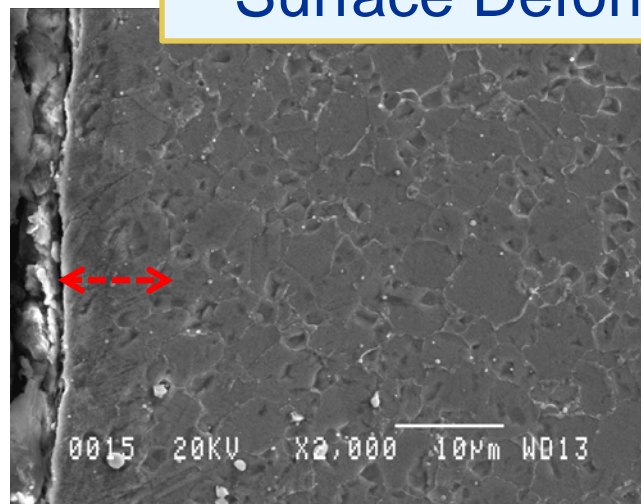


Speed	Sharp			Dull		
	Ra	Rq	Rz	Ra	Rq	Rz
Slow	1	1	1	0.77	0.83	0.99
Medium	0.88	0.90	0.92	0.75	0.72	0.82
Fast	0.90	0.93	0.96	0.45	0.50	0.66

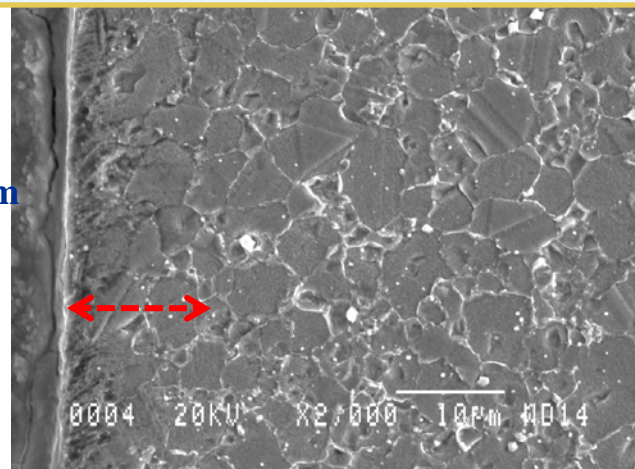
Normalized

- Surface roughness analysis performed on each specimen.
- Sharp broach tooling produced a rougher surface finish than dull tooling.
- Increase in the dull tooling machining speed reduced roughness.

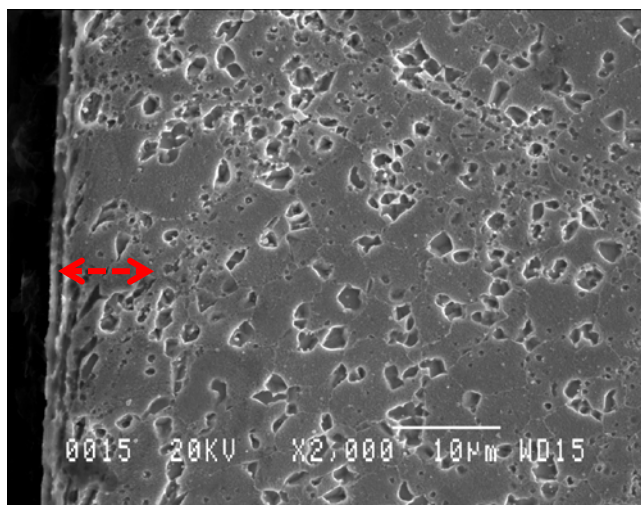
Surface Deformation Caused by Broaching



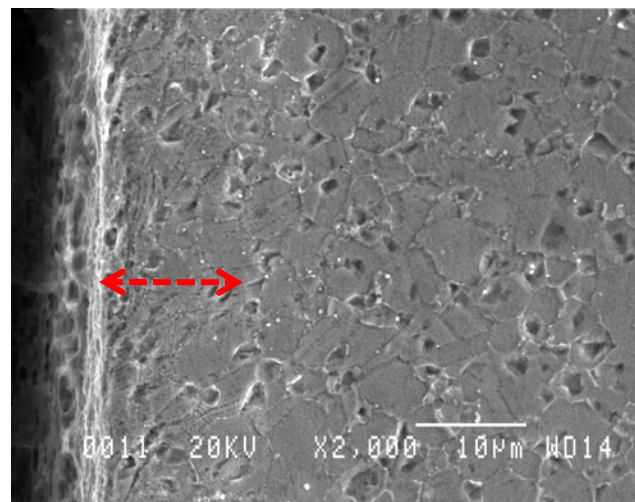
Sharp/Medium



Sharp/Fast



Dull/Medium



Dull/Fast

Broach Direction

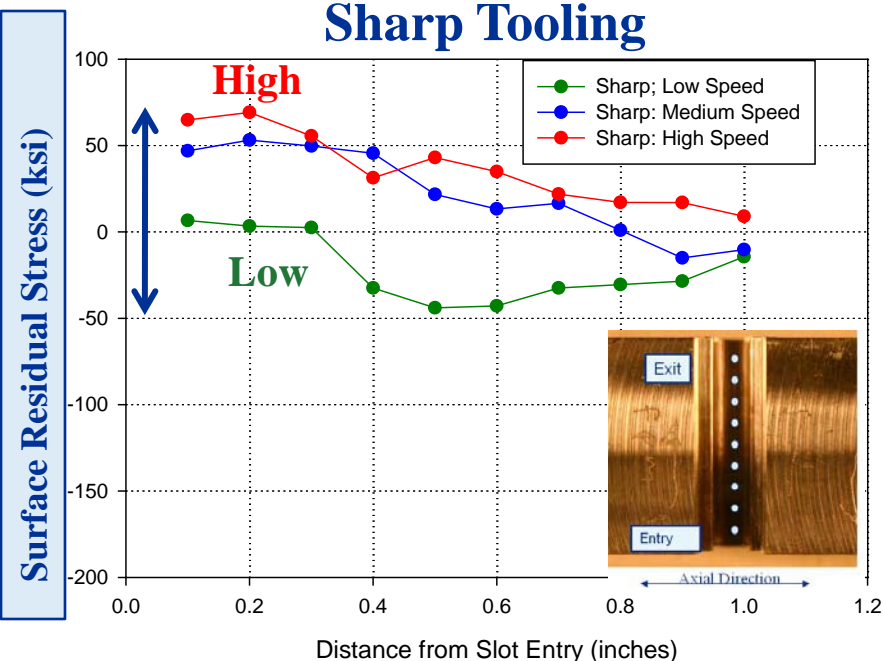
- Some surface damage due to broaching visible for all conditions.
- Higher speeds appear to cause more extensive surface deformation.
- No white surface layer detected – over aggressive machining.



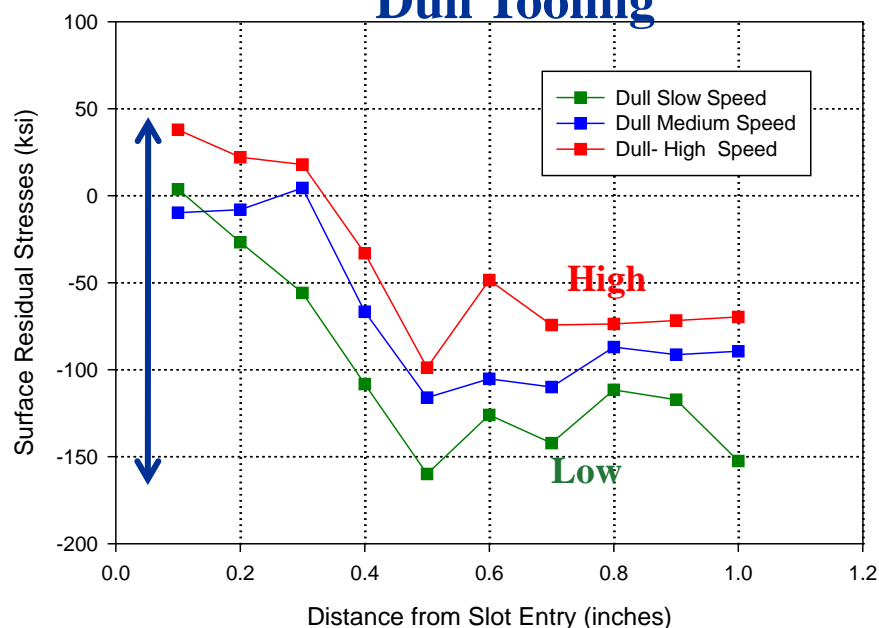
Surface Residual Stress Profiles as a Function of Distance From Slot Entry

Su

Sharp Tooling

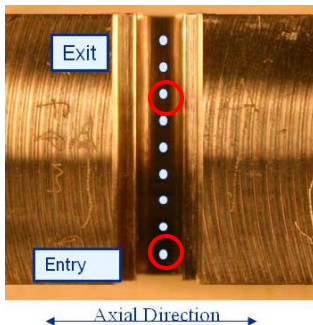
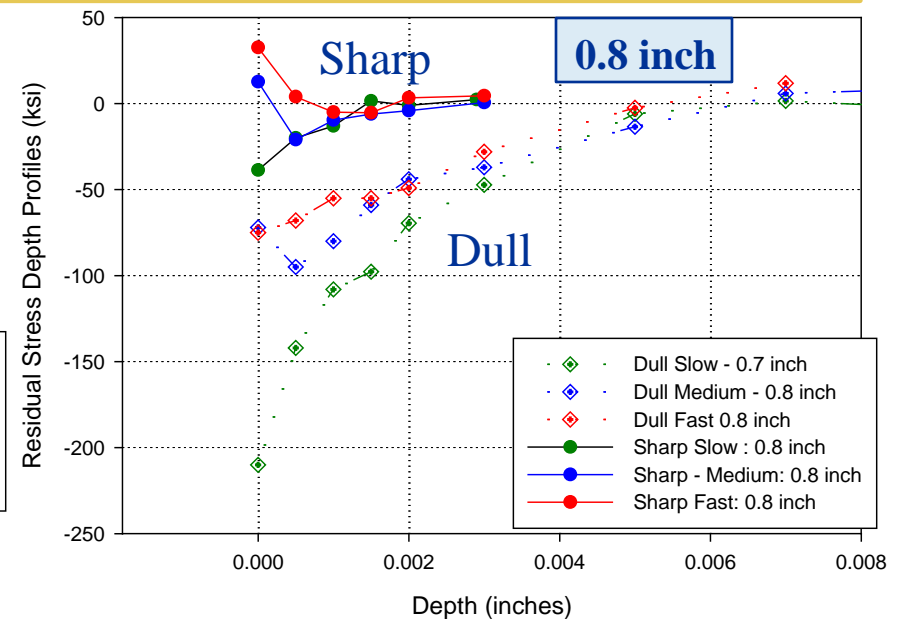
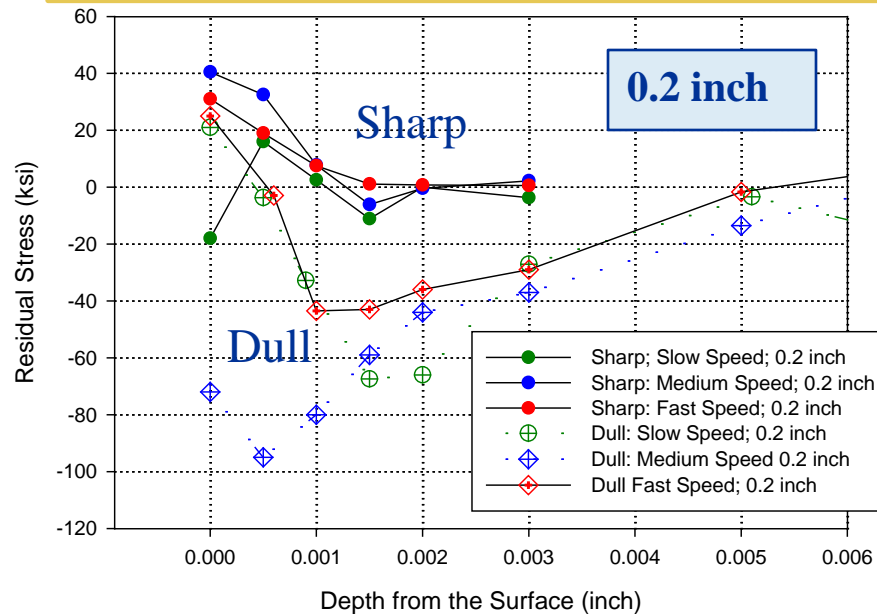


Dull Tooling



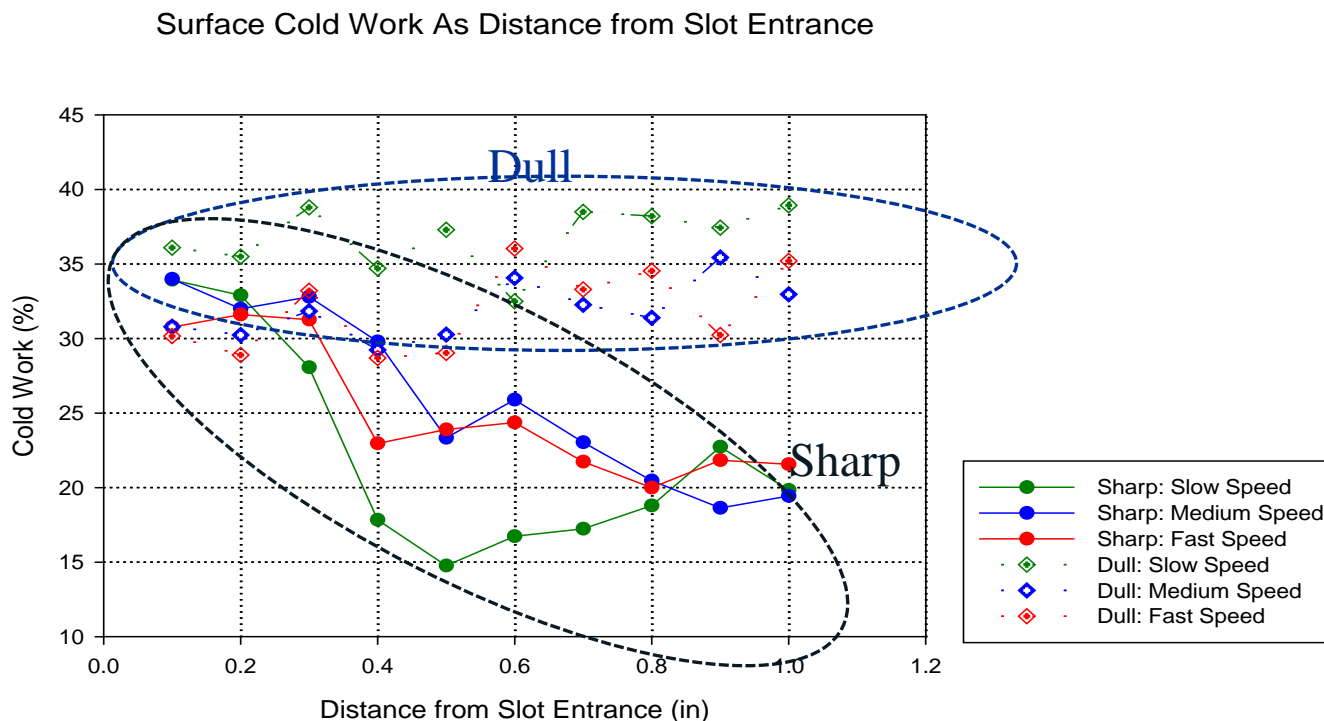
- Residual stresses not uniform across the broach slot - highest at the tool entry point.
- Sharp tooling produced considerably higher residual stresses than dull tooling.
- For both sets of tooling, lowest broaching speed resulted in the lowest (most compressive) residual stresses.
- Dull tooling produced significantly larger range of residual stresses.

Residual Stress Depth Profiles at 0.2 inch and 0.8 inch Slot Locations



- Residual depth profiles for the dull tool set are substantially more compressive than sharp tool set.
- Slower speeds typically resulted in lower (more compressive) near surface residual stresses.
- Compressive stresses depths up to 0.005 inch (dull tools).

Surface Cold Work Percent as a Function of Distance from Tool Entry

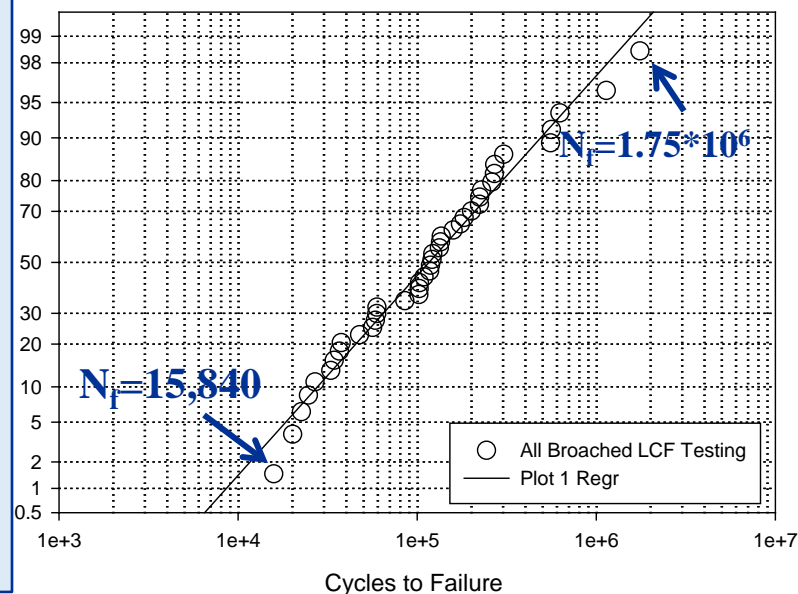


- Overall, dull tooling produced higher amount of cold work which was relatively uniform across the slot thickness.
- Sharp tooling exhibited higher % C.W. on the surface which decreased with distance from entry.

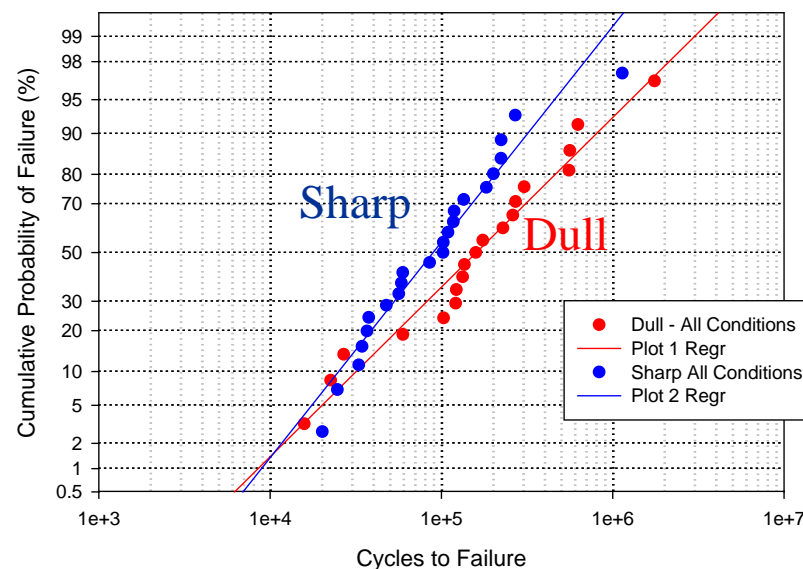
LSHR Configured LCF Specimen Results at 1200°F in Terms of Cumulative Probability Plots

Cumulative Probability of Failure (%)

All Broached Conditions

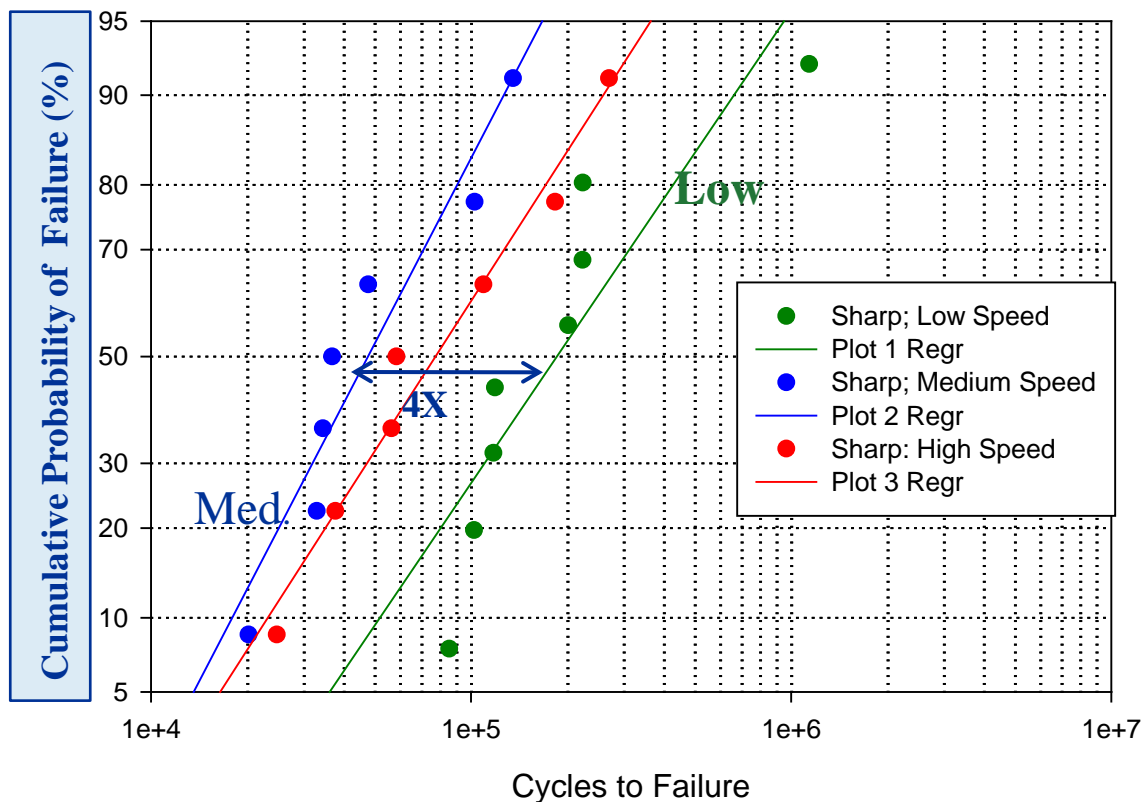


Dull and Sharp Tooling Separated

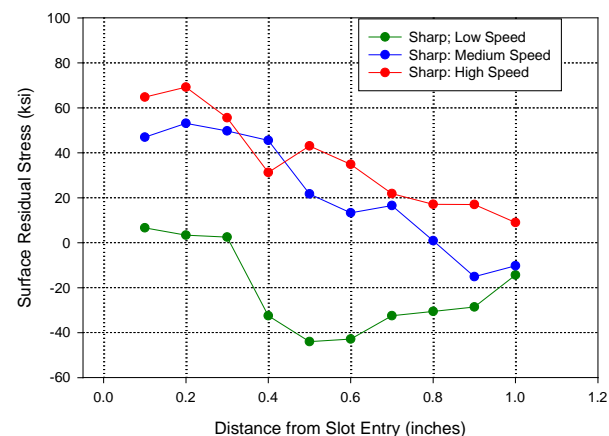


- Fatigue testing resulted in over 2 orders of magnitude spread in LCF lives.
- The dull tooling resulted in ~2X greater **mean** LCF lives and **larger scatter** than sharp tooling.

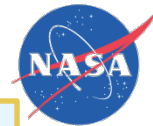
Sharp Tooling- Effect of Broaching Speed on LCF Life



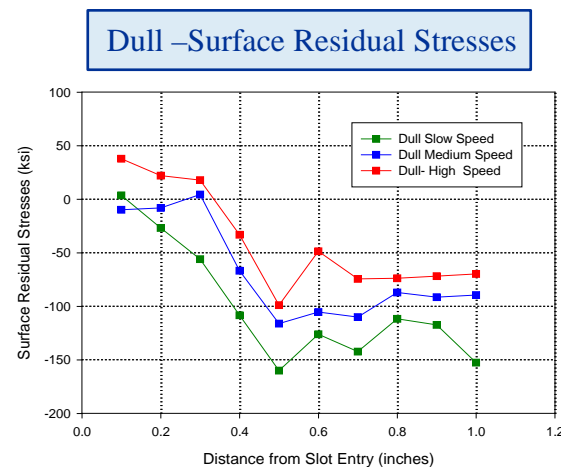
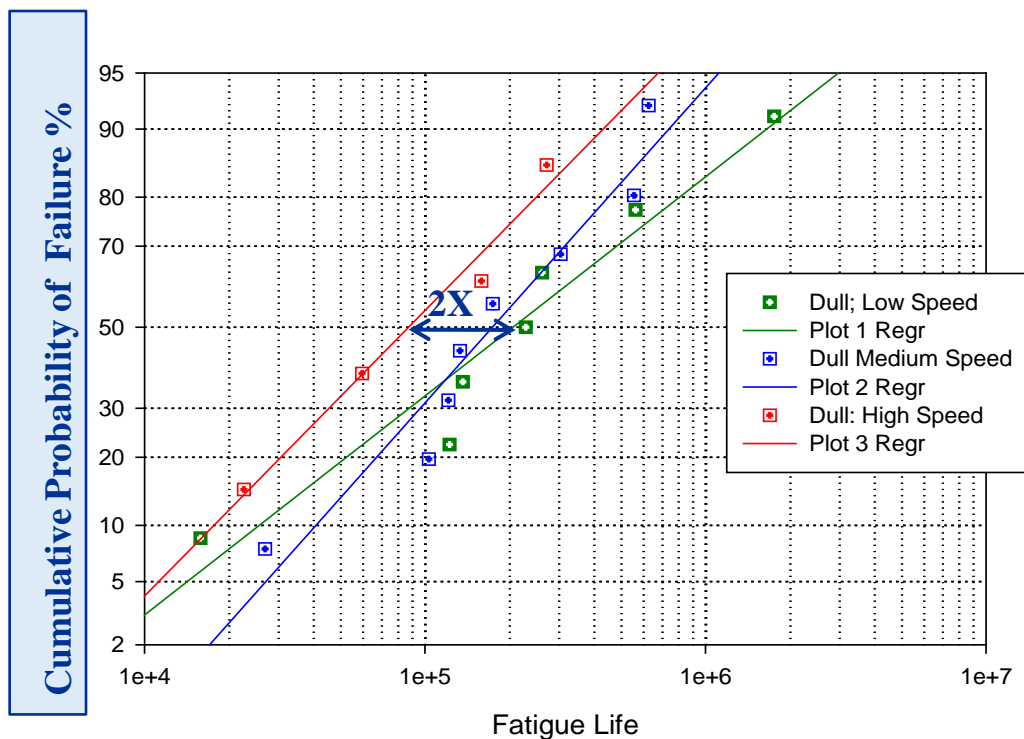
Surface Residual Stresses Measured as a Function of Distance From Slot Entry



- Low broaching speed had highest mean LCF life for the sharp tooling
- This condition also exhibited the most compressive surface residual stresses for sharp tooling.

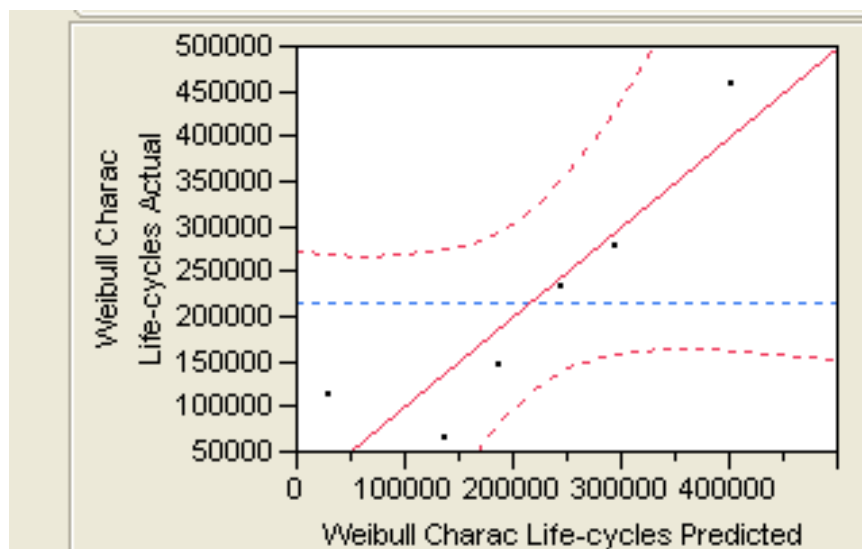


Dull Tooling- Effect of Broaching Speed on LCF Life



- Mean life of the dull tool set no more than ~2X variability.
- High speed broaching resulted in the lowest mean LCF lives.
- High speed broaching resulted in highest (less compressive) residual stresses.
- Lower variation in mean LCF life corresponds to smaller differences in residual stresses between various speeds in comparison to sharp tooling.

Parameterized Statistical Model Developed Relating Broaching Parameters to LCF Life and Scatter in Life



$$\underline{R^2=0.82; R^2_{adj.}=0.71}$$

Weibull Characteristic Life= $215442-107393 \times \text{Speed}+78833 \times \text{Wear}$
Weibull Slope= $1.2 -0.303 \times \text{Wear}$ ($R^2=0.75; R^2_{adj.}=0.69$)

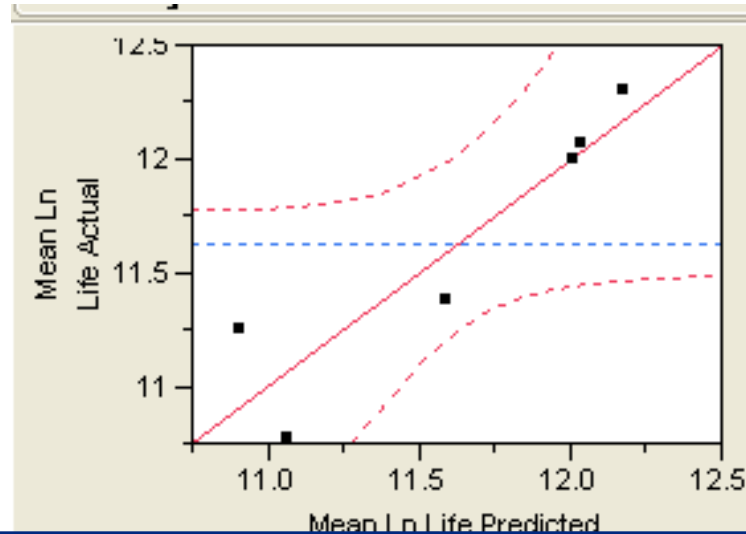
Wear: Sharp=-1; Dull=1 Speed: Low=-1; Medium=0; High = 1

- Characteristic LCF life most strongly increased with decreasing speed, and also increased with increasing wear.
- Increase in wear strongly correlated to increase in scatter.

**Preliminary statistical analysis – more robust analysis in progress*



Multi-Variate Linear Regression Performed to Relate LCF Lives to Residual Stresses and Cold Work

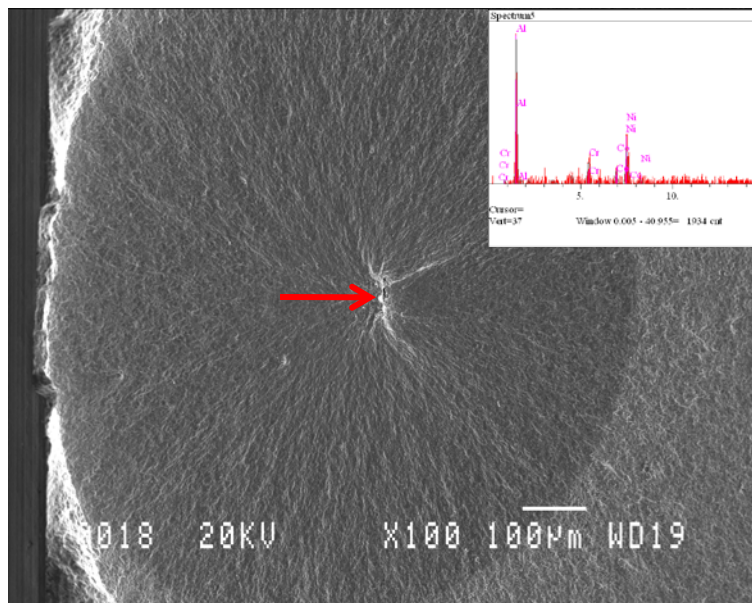


$R^2=0.84;$
 $R^2_{adj}=0.74$

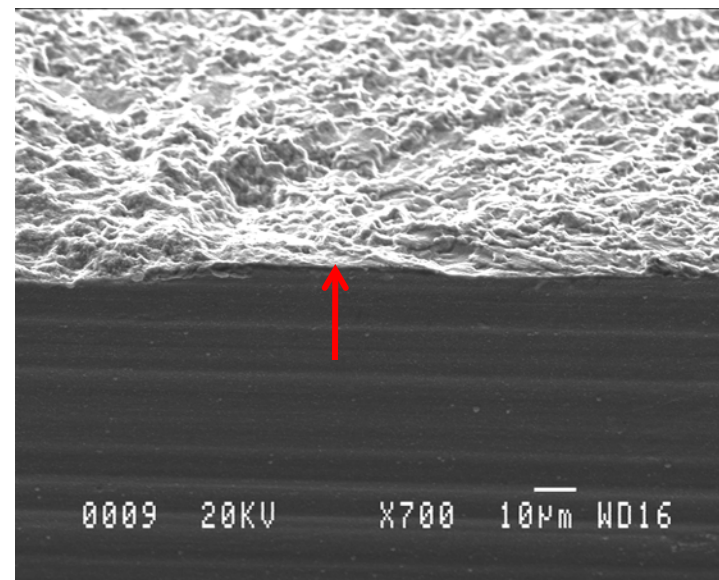
**Mean Ln Life= $13.3-0.0157 \times \text{Residual Stress-ksi}$
- $0.07 \times \text{Cold Work-\%}$**

- Mean life significantly increased as surface residual stress became more compressive and cold work decreased.
- Change in residual stresses was the strongest predictor of LCF life.

Fractography Performed on All Failed Specimens



Failure from a subsurface alumina inclusion



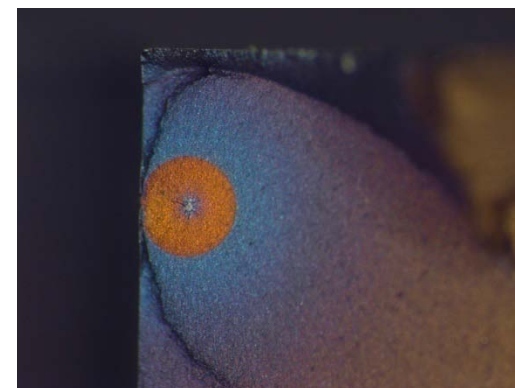
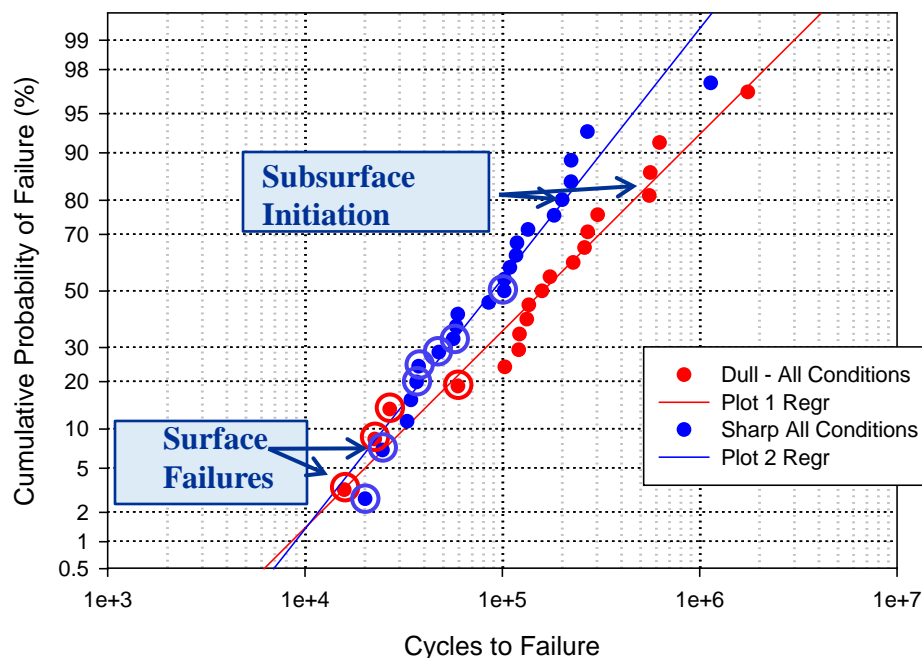
Surface initiation from a broaching groove

- Internal initiations originated at subsurface inclusions (mostly alumina inclusions; few zirconia inclusions).
- Broaching grooves were sites for initiation and growth of majority (not all) of the surface initiated specimens.

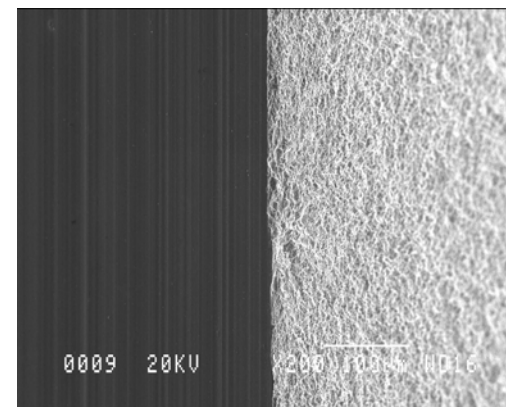
Location of the Initiation Site Related to LCF Life

LSHR Broached LCF Testing
1200°F; Max Net Stress=140 Ksi

Cumulative Probability of Failure (%)



Subsurface inclusion initiation



Surface machining groove initiation

- For both dull and sharp tool sets, surface initiation locations resulted generally in much shorter lives than internal initiations.
- Majority of the failures for both tool sets initiated from subsurface inclusions.



Summary

- **Production tooling was used to evaluate the effect of broaching machining parameters on surface integrity and LCF behavior of the LSHR P/M disk alloy.**
- **Variation in broaching parameters and the corresponding changes in surface response produced up to two orders of magnitude spread in LCF lives.**
- **Increase in tool wear was found to increase the mean LCF life but it also increased the scatter in LCF lives. Decrease in the machining speed increased the mean LCF lives.**
- **Mean LCF life significantly increased as surface residual stresses became more compressive and cold work decreased. Changes in the residual stress distributions were found to be the most important predictor of fatigue lives.**
- **Statistical models were developed which captured the relationship between the broaching parameters, residual stress distributions, cold work and fatigue life.**